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HIGH FLUX HEAT EXCHANGER

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EDWARD M. FLYNN
MICHAEL J. MACKOWSKI

MCDONNELL DOUGLAS MISSILE SYSTEMS
P.O. BOX 516
ST. LOUIS, MO 63166

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Jerry E Beam

JERRY E. BEAM
Section Chief
Thermal Technology Section

B L McFadden

B.L. McFADDEN
Chief
Power Technology Branch

Michael D Braydich

MICHAEL D. BRAYDICH, Lt Col, USAF
Deputy Chief
Aerospace Power Division
Aero Propulsion & Power Directorate

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Edward M. Flynn
Michael J. Mackowski

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St. Louis, MO 63166

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13. ABSTRACT (Maximum 200 words)

This interim report documents the results of the first two phases of a four-phase program to develop a high flux heat exchanger for cooling future high performance aircraft electronics. Phase I defines future needs for high flux heat removal in advanced military electronics systems. The results are sorted by broad application categories, which are: 1) commercial digital systems, 2) military data processors, 3) power processors, and 4) radar and optical systems. For applications expected to be fielded in five to ten years, the outlook is for steady state flux levels of 30-50 W/cm^2 for digital processors and several hundred W/cm^2 for power control applications. In Phase II, a trade study was conducted on emerging cooling technologies which could remove a steady state chip heat flux of 100 W/cm^2 while holding chip junction temperature to 90 °C. Constraints imposed on heat exchanger design, in order to reflect operation in a fighter aircraft environment, included a practical lower limit on coolant supply temperature, the preference for a nontoxic, nonflammable, and nonfreezing coolant, the need to minimize weight and volume, and operation in an accelerating environment. The trade study recommended the Compact High Intensity Cooler (CHIC) for design, fabrication, and test in the final two phases of this program.

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FOREWORD

This report presents results developed by McDonnell Douglas Missile Systems Company (MDMSC) under Air Force Contract F33615-90-C-2054 "High Flux Heat Exchanger." This development program was conducted under sponsorship of the Air Force Wright Laboratory, with Dr. Jerry E. Beam and Mr. Angel S. Reyes, POOS, as Project Managers. The program is divided into four phases:

1. Cooling Requirements for Future Avionics
2. Cooling Concept Trade Study
3. Cooling Concept Detailed Design
4. Fabrication, Test, and Data Analysis

This interim report documents the results of the first two phases.

This program was managed at MDMSC by Mr. Michael J. Mackowski and Mr. Brian K. Bennett. Mr. Mackowski also performed the technical effort in Phase I. The Principal Investigator was Mr. Edward M. Flynn.

Contributions of data from the following sources are acknowledged: Allied Signal; Convex Computers; Coriolis Corp; Cudo Technologies; Frisby Airborne Hydraulics, Inc.; General Dynamics; Honeywell; Hughes Aircraft; J. S. DeWeese Co.; Lawrence Livermore Laboratory; Lockhart; Marlow Industries, Inc.; Microelectronics and Computer Technology Corp.; Motorola; Purdue University; Sundstrand Aerospace; Texas Instruments; Thermacore, Inc.; 3-M; Triangle Research and Development Corp.; and Westinghouse.

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INTRODUCTION

1.1 Background

Modern aerospace systems designers are facing the challenge of effectively utilizing new generation electronic systems which offer lower costs and improved performance while maximizing aerospace vehicle availability. New architectures, systems, and components offering significant improvement over their predecessors have been developed. However, significant gaps in existing hardware do not allow the potential of these advances to be fully realized. Modern systems use electronic components with functional densities increased over several orders of magnitude, yet with only incrementally improved reliability. The net result is that, although the reliability of the individual components has improved, the far greater number of components decrease the system reliability. Cooling is a prime example of an applied technology lagging behind the requirements of electronic systems. With the advent of VHSIC technology and the power increase in switching devices, thermal densities have dramatically risen, but new methods capable of dissipating this thermal load need to be developed. Conventional solutions, such as air or liquid convection cooling, are heavy and bulky. Future platforms offering combinations of high-speed and/or low-observability will require avionics cooling systems that minimize the use of external ram or bleed air. Current conduction cold plate technology limits the power dissipation to roughly 30 to 40 W on each SEM-E printed circuit board (PCB), while recently developed flow-through boards can handle about 200 to 400 W per board. These boards limit the local heat dissipation at individual devices to about 10-15 W/cm^2. Within the next five to ten years, local heat load at the device is projected to increase to about 30 to 50 W/cm^2 for digital processors and to several hundred W/cm^2 for power processors. Therefore, development of novel cooling techniques is needed to provide waste heat removal, temperature control, and reliability improvement.

1.2 Objective

The objective of this program is to analyze, design, develop, and demonstrate a novel high flux heat exchanger for cooling future high performance electronics. The results of the first two phases of this four-phase program are reported in this interim report. The objective of Phase I is to determine future needs for high flux heat removal in advanced avionics systems. The objective of Phase II is to survey emerging cooling technologies, assess their capabilities against the avionics cooling requirements established in Phase I, and to recommend a single concept for design, fabrication, and test in Phases III and IV.

Specifically, this program aims for the following advancements in avionics cooling technology:

1. Using a cooling concept with proven feasibility but limited development (e.g., testing limited to cooling of a single heat source), to scale up to a full circuit board with multiple, high intensity heat sources.

2. To redesign the concept for suitability in an aircraft operating environment. This, for instance, could require changing coolants from a

2. To redesign the concept for suitability in an aircraft operating environment. This, for instance, could require changing coolants from a thermally desirable coolant such as water to a thermally poorer but better-suited coolant for aircraft such as poly alpha olefin (PAO)

3. To demonstrate heat removal capabilities for aircraft avionics significantly greater than those obtainable with currently used heat exchangers.

4. To demonstrate high heat flux capability *and* high packaging density (i.e., to not rely on extensive fin area for heat removal).

1.3 Summary

1.3.1 <u>Future Requirements Study</u> - An industry survey was performed to determine future needs for high flux heat removal in advanced electronics systems. The focus was cooling technology development requirements for military avionics systems. Commercial electronics suppliers were included because many high power devices are being developed in that part of the industry. The results are sorted by broad application categories, which are: 1) commercial digital systems, 2) military data processors, 3) power processors, and 4) radar and optical systems. For applications expected to be fielded in five to ten years, the outlook is for steady-state flux levels of 30-50 W/cm^2 for digital processors and several hundred W/cm^2 for power control applications using advanced MOSFETs or MOS-controlled thyristor technology.

1.3.2 <u>Cooling Concept Trade Study</u> - Evaluations were made of emerging cooling technologies which could remove a steady state chip heat flux of 100 W/cm^2 while holding chip junction temperature to 90 °C. Several constraints were imposed on the cooler due to the intended application of cooling fighter aircraft electronics. Constraints included a practical lower limit on coolant supply temperature, the preference for a nontoxic, nonflammable, and nonfreezing coolant, the need to minimize weight and volume, and operation in an accelerating environment. Evaluation factors included aircraft system impact, cooler development status, and qualitative assessments of life cycle cost, reliability, maintainability, and safety. Seven concepts were identified which could meet the cooling requirements, and were investigated in detail in order to make assessments against the evaluation factors. The Compact High Intensity Cooler (CHIC) was selected for design, fabrication, and test in Phases 3 and 4 of this program.

SECTION 2

FUTURE REQUIREMENTS STUDY

A survey of electronics industry and military avionics component suppliers and system developers was performed to determine future requirements for high flux thermal control technology. Existing military avionics systems primarily use passive cooling techniques for thermal management. Future systems are expected to have higher power dissipation requirements, and the technology to handle higher heat loads needs to be developed. There are already several efforts underway, such as the Air Force Advanced Aircraft Avionics Packaging Technology (AAAPT) program, to accommodate the thermal problems generated by large numbers of small heat loads (each less than about ten watts). But there is little work in progress to handle electronic components that generate high localized heat fluxes on the order of 100 W/cm^2 or more. This led the Wright Laboratory Aero Propulsion and Power Directorate to initiate this effort to develop new concepts in high flux heat exchangers.

This section summarizes the requirements analysis portion of that program. It is not intended to be a systematic survey of all electronic thermal management needs, but rather a search to identify applications that have very high localized flux problems. Complicating this issue are the demands of military avionics systems, which have severe operating environments plus a renewed emphasis on reliability, ease of maintenance, and low cost. Therefore, the operational and packaging aspects of the high flux devices were also investigated.

The survey process consisted primarily of phone interviews with device manufacturers and users. Technical papers, books, and product data sheets were also reviewed. The results are sorted by broad application category, as follows: 1) commercial digital systems, 2) military data processors, 3) power processors, and 4) radar and optical systems. A summary is presented in Table 1.

2.1 Commercial Digital Systems

2.1.1 <u>Processors</u> - Some thermal management researchers anticipate that as digital processors increase in speed and throughput, but decrease in size, the power dissipated in these devices will rise to the order of 100 W per device. As the size of these chips is on the order of 1 cm on a side, the resulting flux density of 100 W/cm^2 presents a challenging thermal problem [1]. However, few existing devices dissipate more than 20 W to 30 W, and the suppliers contacted could not predict with confidence that flux levels would ever reach the 100 W level.

The largest heat loads in digital data processing devices are from central processor units (CPUs) and gate arrays, which are customizable processors. An example of a state-of-the-art, high-performance gate array is the Mitsubishi M6008X which has 400,000 working gates [2]. This device is designed to operate with a maximum heat dissipation of 22 W. A high performance CPU, such as the Intergraph C411, uses 1.0-micron CMOS and runs at 50 MHz, yet consumes only 3.5 W. The MIPS R3000, a 32-bit CPU, operates at over 30 MHz, and is also in the 4 W range [3]. The MIPS R4000, an advanced 64-bit processor, is not expected to use significantly more power.

Table 1. Summary of Future Electronics High Flux Cooling Requirements

DEVICE	AVE. FLUX, W/cm^2	PEAK FLUX, W/cm^2	APPLICATION
MCTs for power converters	>100	>250	Power conversion for "More Electric Aircraft"
GaAs wafer-scale RF array	100	100	Advanced radar/sensors
Klystrode RF amplifier	60	60	Neutral particle beam
Gyro-klystron RF amplifier	50	50	High-power radar
Laser diode stack	25	>50	Laser communications/sensors
400k gate array	15	22	Advanced data processors
Digital multi-chip modules	1-5	20	Advanced data processors
Pave Pace SEM-E modules	1-5	1-5	Multirole fighter avionics
"Aladdin" processor board	1-5	1-5	Smart munitions guidance processor
Power supplies, SEM-E format	1-5	1-5	Aircraft avionics
32-bit RISC processor	1-5	1-5	Missile guidance system
Supercomputer circuit board	1-5	1-5	Commercial mainframe computer
Power MOSFET	1	50	Missile fin actuator drive*
Radar TWT	1	5	Fighter aircraft radar
Power transistor	<1	<5	Spacecraft battery charger
30k gate array	<1	<1	Missile guidance processor

Notes:
1. Items are sorted by average heat load
2. Average heat flux refers to the sustained system average load.
3. Peak flux as measured over the device footprint, not a hot spot on the device.
*Very low duty cycle

Future chips with higher performance will need to use lower voltages to reduce feature sizes to less than one micron. When the voltages are lowered, the power will go down. Even if gate count per chip goes up, it appears that total power per chip will not increase a great deal. Most manufacturers expect that processor performance will continue to increase while power consumption will remain at manageable levels (under 30 W).

The anticipated heat load from high performance gate arrays can easily be misunderstood. For example, when speed is traded off against power, the Mitsubishi M6008X is rated at 6.0 µW/MHz/gate. If one multiplies this value by the total number of practically usable gates at the maximum speed of 100 MHz, the total power dissipated is as given in Eq (1):

$$((0.000006\ \mathrm{W})/(100\ \mathrm{MHz})/\mathrm{gate})) \times (250000\ \mathrm{gates}) \times (100\ \mathrm{MHz}) = 150\ \mathrm{W} \qquad \mathrm{Eq}\ (1)$$

This is unrealistic, however. All of the gates will not be toggling at the same time. Perhaps only 20% of a gate array will be operating at the maximum clock rate. This device is only available in a plastic case rated for a maximum of 22 W, as previously noted.

One could still project that future CPUs and gate arrays might generate more than 60 W of heat, but hard data to support power levels above that has not been found. Because gate arrays are slower and require more power and real estate than custom chips, they are not likely to be used in compact military avionics.

2.1.2 Mainframe Computers - Although the Cray-2 and Cray-3 supercomputers are actively cooled via total liquid immersion [4], the trend is toward more passive approaches. The Cray machines dissipate hundreds of kilowatts in a five by three foot enclosure which requires liquid cooling. In most supercomputers, the heat generated by each individual chip is actually low, but the total thermal load is high because a large number of chips is used in a very compact arrangement. Most future supercomputers will use lower-powered chips, but special high-performance systems may have speed and packaging requirements which will generate heat loads high enough to demand active cooling.

Supercomputers manufactured by Convex Computers have the unique feature of being cooled without liquids, relying completely on forced air. They can accommodate 500 W per 18- by 36- inch board in this fashion. Using low-powered GaAs chips, the typical heat generated per chip is 30 W, and they are spaced far enough apart to minimize the average heat load.

Multi-chip modules (MCMs) are becoming commonly used in commercial digital processing applications, and are slowly making their way into military electronics. MCMs have several chips mounted on a common substrate, typically a few inches square. The chips are connected via microwires and/or traces laid into the substrate. This achieves much faster communicating speeds among the chips, improving overall processing speed significantly.

Motorola reports manufacturing an MCM (about 4 inches by 4 inches in size) that can accommodate a heat load of up to 500 W [5]. The resulting flux density is 14 W/cm^2. Shown in Figure 1, the MM16M5ECL can contain several ECL or BiCMOS chips that could dissipate around 60 W each. Forced air or liquid is used for cooling. The VAX 9600 uses an MCM which dissipates 500 W. The general trend, however, is away from devices with very high flux densities, such as 100 W/cm^2, and toward more efficient processors.

The Microelectronics and Computer Technology Corporation (MCC) is a consortium of several large electronics, computer, and defense firms that work together on advanced computing concepts. They are developing a microchannel-cooled multichip circuit board, which is part of a $20 million effort they have underway on microcircuit packaging. [6] This type of industry activity demonstrates a concern about thermal management problems.

2.2 Military Data Processors

2.2.1 General - Most data processors in current military avionics systems (or projected for use in the next 5 to 7 years) are silicon devices with relatively low flux levels. They generally dissipate on the order of 2 to 5 W/cm^2 per device, with total circuit board loads of 10 to 20 watts. Board configurations vary, but many are SEM-E format or similar, with a metal heatsink core adequate to perform the thermal management passively. An example of this is the 1750A single board computer shown in Figure 2.

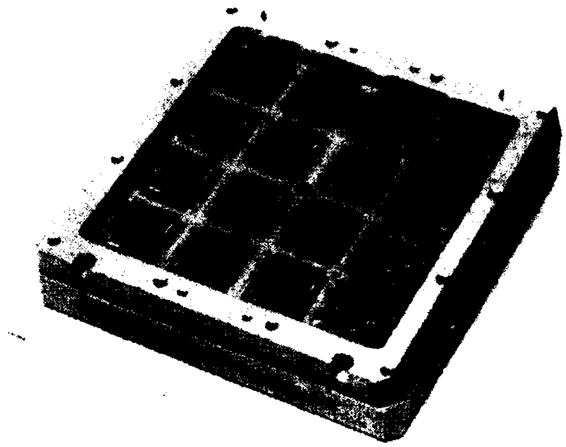

Figure 1. Motorola MM16M5ECL custom MCM. (Photo courtesy Motorola.)

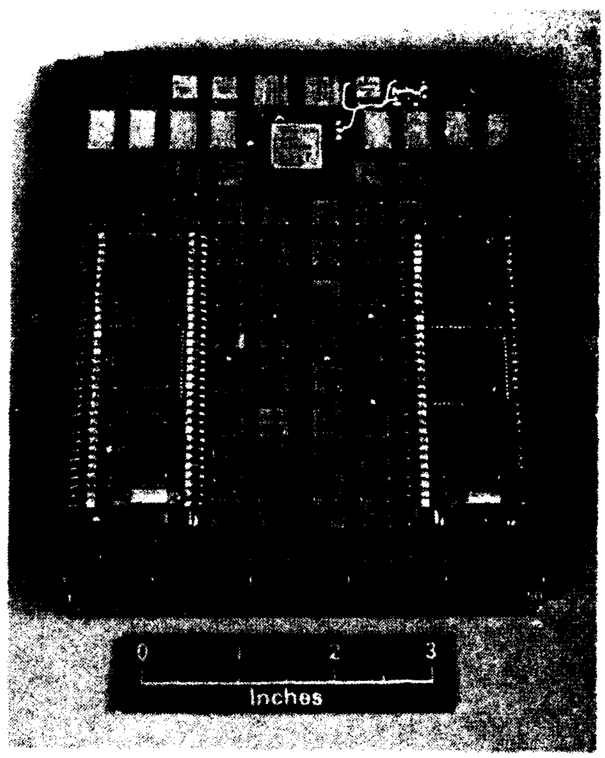

Figure 2. 1750A single board computer (Photo courtesy McDonnell Douglas Electronic Systems Company.)

Existing systems using VLSI (Very Large Scale Integration) operate at a frequency of 10 MHz and dissipate as much as 20 watts per board. VHSIC (Very High Speed Integrated Circuits) class parts will run at 40 MHz, which could result in an increase in heat load by a factor of 2 to 4. Future digital systems that use VHSIC II products are projected to push the heat load up by another factor of 2 to 4, putting the upper end at (20 W x 4 x 4) = 320 watts.

Gallium arsenide (GaAs) chips are beginning to replace silicon because of their higher speed and lower power. But GaAs is a poor thermal conductor, which makes heat spreading difficult within the chip, as the heat is generated at very tiny locations on the chip. CMOS (silicon) chips are very low power, and are not quite as fast as GaAs. But the lower cost of CMOS devices, coupled with their low power requirements, makes them more popular than GaAs at this time. The Motorola 68040 CPU is a CMOS chip that has over one million devices, yet consumes only one watt of power. BiCMOS is a compromise technology that provides increased speed at the expense of somewhat higher power, but the power increase is only fractional. ECL (emitter coupled logic) is the fastest silicon-based technology, using bipolar rather than MOS switches. Large ECL arrays (multipurpose silicon chips often used for memory or custom processors) can have several million devices per chip, yet require only about 5 watts. Extremely large ECL arrays have been proposed that might reach the 80 to 100 W/cm^2 level, but their use on military systems is many years into the future, and several avionics designers interviewed on this topic had difficulty imagining how such devices might be used. Large GaAs processors may also eventually reach that flux level, but it will be ten years or so before those systems are developed, according to most sources. 32-bit RISC processors (at least some of which are GaAs) are being used now in a few missile data processors, and these require only a few watts each.

Many military avionics systems presently in development use general purpose off-the-shelf processors. Actual operational systems will likely use custom chips, which will result in a lower total chip count (because the custom chips package their functions more efficiently and can operate faster) which will also ease packaging constraints. Additionally, many missiles and other weapons have such unique requirements that general purpose chips will not perform adequately. Custom chips will be required, and these can be tailored for higher speed and lower power than those used in development and prototyping programs. Higher density chips are also now being designed to operate at lower voltage levels, resulting in lower overall power requirements.

2.2.2 **Aircraft Applications** - The Air Force Pave Pace program is intended to identify, and then develop, the standard modular avionics which will be needed for future aircraft, specifically focussing on the MultiRole Fighter (MRF). Pave Pace is an 18-month program that began in March of 1990 with three prime contractors. It involves a wide-ranging technology assessment and has goals of reduced cost and greatly improved reliability.

The portion of the Pave Pace study performed by the McDonnell Aircraft Company considered the architectural requirements for future avionics systems, and they have developed a building block concept for future avionics suite designs. This resulted in a functional breakdown into about 200 SEM-E level line-replaceable modules (LRMs) which would be needed for the entire MRF avionics suite. Many of the units have heat dissipation of less than 40 W, which is the JIAWG (Joint Integrated Avionics Working Group) standard allowable upper limit for SEM-E boards. In general, the localized heat flux is low, and can be handled by existing passive approaches. However, about half of the LRMs would dissipate over 40 W, and therefore would require some sort of liquid cooling. The units with a need for high total heat load cooling (in this particular study) are primarily the integrated core processors. [7]

To support the Pave Pace program, the USAF began a complimentary program, called Advanced Aircraft Avionics Packaging Technology (AAAPT), to consider how to package these LRMs. There were three contracts awarded, including one to AT&T/Bell Labs to develop active cooling technology for the LRMs. This program developed a liquid flow-through heat exchanger with dripless quick-disconnects that would meet the JIAWG standards for form, fit, and function. These were built and tested at 200 W per board dissipation while holding a junction temperature at 80°C. A low-cost stamped aluminum heat exchanger was imbedded in the board, and it passed life, vibration, and environmental tests [8]. There are now plans to build and test a double-width (two-slot) LRM version having multi-chip modules for a 400 W total heat load.

2.2.3 **Missiles and Smart Weapons** - A far-term application which is currently in the early study phase is automatic target recognition (ATR). Such an application will require massive computing power to be packaged into missiles and small munitions. If higher data processing throughput is available, the software is much easier to write, thus reducing cost. This will cause an ever-increasing need for greater throughput capability. This is an area which may eventually drive the processing and packaging requirements together such that novel thermal management techniques will be required, but the numbers are difficult to quantify at this time.

To achieve one billion bits-per-second processing throughput capability in a package suitable for advanced missiles and smart munitions, DARPA began the Aladdin program. This processing capability will be required for ATR and similar missions. The two prime contractors are Honeywell and Texas Instruments. By using 32-bit RISC processors, which dissipate 2 to 3 watts per chip, and MCMs, overall heat loads remain manageable at about 65 W for the total 6-inch long by 4-inch diameter package.

Guidance electronics for SDI missions, where processing for imaging/data collecting/targeting is more intense, might use several MCMs to achieve the required speed and throughput. For a conceptual study done for an SDI application, heat dissipation was estimated to be about 10 to 15 W per chip, but over a hundred such chips were needed, suggesting a need for a liquid cooling approach. Flux levels of 100 W/cm^2 were deemed unlikely in that application. Even a systems such as Brilliant Pebbles, which has been touted as having tremendous computational capabilities, may not require more than 100 W per board.

2.2.4 **Summary - Data Processors** - The intense interest in thermal management of digital systems, evidenced by the many technical papers and research being performed in this area, appears to be driven by high total board loads, not localized device loads. Designers of military avionics predict that the total power per SEM-E type board may go as high as 200 - 400 W for digital systems. But localized heat flux is likely to be relatively low, not much more than 30 to 50 W/cm^2 for most devices. While no chip manufacturer or avionics supplier was willing to predict that 100 W data processing chips will be common in future military avionics systems, it is possible that such a cooling requirement may eventually be needed for very specialized high-performance digital applications.

2.3 Power Processors

2.3.1 General - Requirements for inverters and motor controller drives were researched by talking to users and system developers, including NASA, General Dynamics, Douglas, Allied-Signal, Westinghouse, and others. Data sheets were also reviewed for high power MOSFETS and Insulated Gate Bipolar Transistors (IGBTs) from several suppliers.

For advanced power supplies using high power solid state devices (SCRs, MCTs, transistors, etc.), the switching devices may be characterized as single-point heat sources with operating temperature controlled by a conductive heat sink. Individual device peak temperature remains the limiting factor in determining operating characteristics. Whatever the cooling method, the thermal resistance of the heat transport system must be small enough to prevent hot spots from occurring at the device-to-cooling-medium interface. Due to operational requirements and limitations, each of these devices must be electrically isolated from each other, further complicating the heat collection process when multiple devices are use, wLich is almost always the case.

2.3.2 Low Voltage Power Supplies - A low-voltage, passively-cooled power supply has been developed for a Pave Pace type (SEM-E format) implementation. This transforms the 270 VDC to lower voltages (±5, +15 VDC, etc.) for distribution to individual circuit boards. Alternatively, smaller converters on each board can convert an intermediate 50 V bus level to the lower voltages used by digital and small signal circuits. A 200 W power supply (waste heat of about 40 W at a 40 ampere output) has been developed for the ATF program. A larger unit, processing over one kilowatt at very high efficiencies, is under development by Texas Instruments. This board typically dissipates about 50 W, and requires liquid cooling.

2.3.3 High Power Systems - Power processing for electromechanical actuators for the More Electric Aircraft initiative will involve high current and high voltages. The use of solid state switching devices, with typical voltage drops of one to two volts, will, in some instances, result in power dissipation of several hundred watts per device. The actuators involved will require 30-40 hp (22 - 30 kilowatts) motors. The power supplies to drive them are generally assumed to use advanced solid state switching devices such as MOS-controlled thyristors (MCTs), which can handle the high current at reasonably high switching speeds. These devices may reach current densities of 150 A/cm^2 or higher, resulting in hundreds of watts of cooling requirement [9]. The overall packaging approach to handle the combination of high voltage, high current, and high heat flux is still being developed.

2.3.4 Neutral Particle Beam - RF output transistors used in a space-based RF amplifier with a 400 kW RF output results in 3 kW waste heat, and must be packaged in a system about the size of a bread box. In the continuous operating mode, these transmitters generate a heat flux of about 60 W/cm^2. Being a space application, packaging constraints will probably be specialized. A cryogenic liquid microchannel cooler may be required, but this would be a very unusual case with limited relevance to other applications in this survey.

2.3.5 Summary - Power Processors - Solid state power switching devices will certainly generate higher heat loads than digital devices. MCTs operate at current densities of 150 to 200 A/cm^2 over an active die area of less than 1 cm^2, resulting in a heat flux of over 400 W/cm^2. Although generally operated in a low duty cycle pulsed mode for inverters and motor controllers, the steady-state heat levels for these devices will still be in the 100 W/cm^2 range. If operated in a continuous mode as a power control switch, for example, a single MCT would generate a continuous heat load of 200 W or more.

In summary, a cooling capability of at least 100 W/cm^2 for power applications is needed. It could even be higher, depending on the application. Unfortunately, for the purposes of this study, the most demanding applications are the ones which are the most poorly defined (because they are usually only concepts rather than existing designs), resulting in an uncertain requirements projection.

2.4 Radar and Optical Systems

2.4.1 Conventional Radar - Existing radar systems are discretely packaged, usually split into an antenna unit, a modulator/exciter (signal generator), a power amplifier for the transmitter, a receiver unit, and a signal processor to sort out the returns. Because the traveling waves tubes (TWTs) can have waste heat levels in the hundreds of watts, they are sometimes directly immersed in an inert fluid. The amplifiers and processors have a much lower heat dissipation, and are cooled via forced air or by mounting the units on coldplates. Despite the high total heat loads, the localized heat flux is generally low, as evidenced by the low ratings of radar systems coldplates, typically 1 to 2 W/cm^2. Because of concerns with leakage and reliability of liquid cooling systems, radar developers are trying to make the power amplifiers more efficient so that conduction or forced-air cooling is all that is needed. Future systems are expected to combine radar subsystems into very compact, high-density assemblies (wafer-scale and microwave monolithic integrated circuits, MMICs), or to divide them into more general functional units which are implemented on standardized LRMs.

2.4.2 Solid State RF Arrays - Newer approaches, such as active arrays based on wafer-scale technology, will require very compact heat exchangers to be built directly into the assembly. In these devices, all of the functions are built into a single monolithic structure. This combines the antenna, the transmit/receive (T/R) modules, and the data processor. The resulting concentrated heat load requires that a liquid cooling manifold be built as an integral part of the assembly. The overall packaging density is limited by the half-wavelength spacing required between the RF elements. This larger area required by the antenna portion then provides greater room in the package for the digital section, thus easing thermal management. As part of the AAAPT program, Westinghouse Electronic Systems Group studied this RF packaging problem.

The cooling need is generated by the R/F elements, the solid state power amplifiers, and the signal processors that analyze the return signal. Another concern is that any significant amount of heat generated can cause physical distortion of the antenna elements, which can distort the beam. The trend now is toward higher power and multiple, narrow beams.

Fortunately, the MMIC devices used can operate reliably at somewhat elevated temperatures (over 100°C), thus easing the thermal control problem somewhat. While a MMIC power amplifier may dissipate at certain locations over 2 kW/cm^2, this occurs over a very small area, and can spread to less than 10 W/cm^2 at the heat exchanger interface. These arrays could include thousands of transmit/receive elements, generating total heat loads in the kilowatts. [10]

2.4.3 **Laser Radar** - Advanced terminal guidance systems for missiles and smart munitions will need to acquire and select targets by matching them with images digitally stored in the missile's guidance system. One way such target recognition can be implemented is with laser radar sensors, which can generate high resolution imaging data and send it to a processor for matching. The data processors for this application will require special cooling considerations, as will the laser diode sources for the optical radar sensors. Current studies indicate that the data processor for such a system will require only 50 W per board, which can be approximately SEM-E in size.

2.4.4 **Optical Sensors** - The U.S. Army Mast Mounted Sight is used on the OH-58D helicopter to peer over the battlefield without completely exposing the helicopter. A processor is used to stabilize the sensor platform (visual TV/IR), perform tracking and targeting functions, and link it the to the weapons systems. A study conducted by the McDonnell Douglas Electronics Systems Company (MDESC) to upgrade this processor to SMT (surface mount technology) GaAs technology resulted in a 40 W per board (two boards total) cooling requirement, which can be met by passive techniques.

2.4.5 **Laser Communications** - Laser diodes used for communications and sensors have high localized flux levels, typically about 25 W/cm^2 [11]. The total area is usually quite small however, and there are seldom many other large heat generating components mounted nearby. Additionally, the packaging and cooling approaches are often rather unique, with only limited relevance to other applications.

2.4.6 **Summary - Radar and Optical Systems** - The most likely drivers for high flux cooling needs in this area will come from active RF arrays and laser devices. Both use new technology that generates very high localized heat loads, and both topics are already the subject of significant research efforts in order to solve their thermal management problems.

2.5 Conclusions - Future Cooling Requirements

Thermal loads for military avionics systems will continue to increase. Power control applications will create the most challenging problems for high flux thermal management systems, while certain high-performance digital systems are expected to have a lesser but still significant need for high flux coolers.

High heat load requirements may be divided into two categories:

1. Systems with many sources of relatively low heat flux (5-20 W each)
2. Systems with very high localized heat flux (>100 W/cm^2)

If only the first case applies to a particular problem being studied, then there is a certain set of thermal management solutions available using existing technology. If the second category also applies, then existing thermal management approaches are unlikely to be practical, and new solutions must be developed. While the majority of applications involving active cooling will require the management of a large total heat load with a low local flux (the first category), there will be very demanding situations in power processing systems where new approaches in high flux heat exchanger technology will be a necessity.

The work which has been reported in this section is also described in [12].

SECTION 3

COOLING CONCEPT TRADE STUDY

In Section 2, the most challenging thermal problems were found to lie with power controllers, with steady-state heat fluxes reaching at least 100 to 200 W/cm^2. Pulsed heat loads of short duration (on the order of a second or less) could exceed 400 W/cm^2. The heat dissipation of future high-performance data processors was predicted to be somewhat lower, with steady-state levels reaching perhaps 50 to 100 W/cm^2. Other areas of military electronics requiring significant cooling are embedded apertures and laser diodes. Methods currently employed to cool avionics cannot meet these projected thermal requirements. These include conduction via metal planes built into the board, natural and forced air convection (often augmented by the use of large fins), currently used cold plates, simple immersion cooling, and currently used heat pipes. Their maximum heat flux capabilities are either too low, or they would require large fin area, thus limiting packaging density.

The task was therefore undertaken to evaluate and trade off emerging cooling technologies capable of meeting the demanding thermal requirements foreseen for near-future avionics.

3.1 Approach

Because advanced fighter aircraft will have power processors, embedded apertures, and advanced digital processors, this system was selected for conducting the trade study concept evaluation. Some cooling concepts have demonstrated heat flux removal rates far in excess of the cooling levels required, but have used water as the coolant. Water is usually unacceptable as an aircraft coolant because it freezes. For concepts not tested with an aircraft-compatible coolant, thermal performance had to be extrapolated from the concept database.

3.1.1 **Evaluation Criteria** - Evaluation criteria are shown in Table 2. The evaluation criteria were given weighting factors reflecting the objectives of this program. For example, a goal was to seek high performance concepts with due consideration to packaging compactness, but without significantly penalizing the thermal performance for the sake of compactness. Reliability, safety, cost, and system weight impact (the latter being an indirect measure of thermal performance) were considered the most important criteria.

3.2 Requirements and Constraints

Concept performance was predicted within the constraints imposed by Air Force fighter aircraft. Evaluation of the candidate heat exchangers took into account standard environmental conditions and other specifications used for fighter aircraft design, such as:

Non-operational and operational temperature extremes
Vehicular accelerations
Toxicity, corrosiveness, and flammability of coolant
Coolant supply temperature

Table 2

Trade Study Evaluation Criteria

CRITERION	WEIGHTING FACTOR
System Weight Impact	0.15
Life Cycle Cost	0.15
Safety	0.15
Reliability of Heat Exchanger	0.15
Development Status - Manufacturing	0.10
Development Status - Testing	0.10
Thickness	0.08
Lateral Size	0.08
Life	0.02
Design Flexibility and Growth Potential	0.02
Total	**1.00**

3.2.1 Coolant Selection

Single-Phase Coolants

An ethelyne glycol/water (EGW) mixture has an acceptably low freezing point. However, ethelyne glycol is corrosive, and its use is often discouraged. Coolanol has been a standard coolant on fighter aircraft, but it is being replaced by polyalphaolefin (PAO) ([13], [14], [15], [16]), which is much less prone to decomposition. The thermal properties of PAO are similar to those of Coolanol and inferior to those of water and EGW.

A potential drawback to PAO is high viscosity at low temperature. The viscosity of PAO is approximately 24 times as great at -40 ^{o}C as at room temperature, and 110 times as high as -54 ^{o}C as at room temperature. Nevertheless, its chemical stability is attractive enough to make it the standard coolant for most future fighter aircraft. Recognizing the rarity of the -54 ^{o}C condition, a -40 ^{o}C cold start condition is sometimes considered for systems using PAO (see, e.g., [17]).

Two-Phase Coolants

As with single-phase coolants, water has the best thermal properties of any practical two-phase coolant, but it usually cannot be used. Ammonia has good liquid thermal properties, and its large heat of vaporization makes it a good choice in two-phase systems. However, ammonia must be pressurized to keep it in the liquid state at moderate temperatures. Toxicity also makes ammonia dangerous. Methanol is frequently used in heat pipes and in two-phase cooling systems because its 65 ^{o}C normal boiling point is ideal for many cooling applications. However, its flammability results in a safety hazard if leaks occur in the system. Dielectric refrigerants such as FC-72 and FC-87 have low freezing points, but poor thermal properties.

3.2.2 Thermal Requirements - Electronic failure rate is well known to increase with temperature. Maximum device junction temperature specifications vary with the type of device, with values ranging typically from 60 °C to 150 °C. A 90 °C maximum junction temperature was selected for this study.

Two requirements were established for heat flux. First, based on the results discussed in Section 2, a steady-state heat dissipation of 100 W/cm^2 was selected as representative of near-future high power avionics components. At this design point, the cooler was required to hold the electronics device junction temperature to 90 °C. The second requirement was for a factor of safety (F.O.S.) of 2.0 on heat flux. The cooler was required to be capable of 200 W/cm^2 heat flux so that it could meet the 100 W/cm^2 requirement if operating at an off-design condition. The 90 °C junction temperature requirement was not imposed at this higher heat flux.

3.2.3 Geometric Configuration - The three applications identified on a fighter aircraft (digital processors, power processors, and embedded apertures) all share certain common design constraints. Embedded apertures and digital processors, especially, require thin heat exchangers. Digital processors are often mounted on electronics boards which are spaced 1.5 cm apart, while space limitation requires tight packaging of embedded aperture components and their cooling devices. With devices often packed in tight arrays, there is little room for heat spreading, so the lateral extent of the heat exchanger must be minimized. Thus, heat exchanger thickness and lateral size requirement were chosen as evaluation factors.

3.2.4 Thermal Resistances - To evaluate the ability of the cooling concepts to maintain 90 °C junction temperature, certain assumptions had to be made concerning various thermal resistances. Fig. 3 shows the thermal resistances between the device junction and the coolant. When the device is not in intimate contact with the coolant, as shown in the drawing, three resistances are present: the junction-to-case resistance, (R-jc); the resistance across the bondline between the device and the heat exchanger or attachment surface, and through this surface, (R-cw); and the resistance between the heat exchanger or attachment surface and the coolant, (R-wf). For concepts using direct coolant/device contact, R-cw is absent.

For all concepts evaluated, R-jc was assumed to be equal to 0.20 °C/(W/cm^2). At the design heat flux of 100 W/cm^2, this thermal resistance implies a temperature drop from junction to case of 20 °C. With the junction temperature requirement at 90 °C, the maximum allowable device case temperature is then 70 °C. For concepts employing direct liquid contact with the device, this is the temperature of the surface contacting the coolant. For boiling concepts, FC-72 is then assumed as the coolant because it is a dielectric and has a normal boiling point of 56 °C.

For concepts employing indirect contact (i.e., nonimmersion concepts or concepts employing attachment surfaces), R-cw was assumed to be 0.20 °C/(W/cm^2). Thus, at the design condition, there is a 20 °C temperature drop from the device case to the surface contacting the coolant. The surface in contact with the coolant is then at a

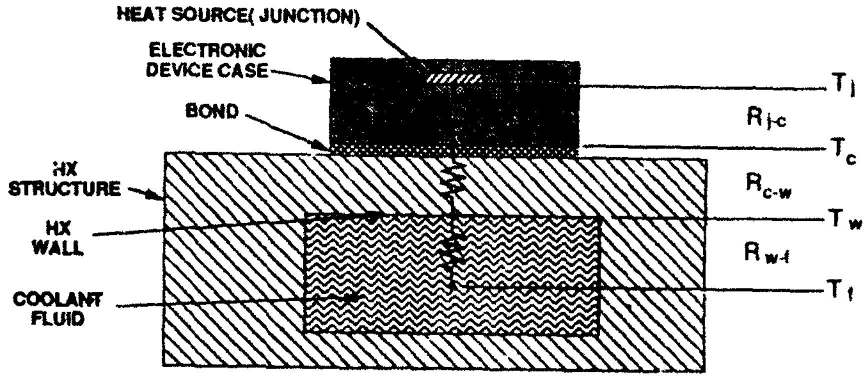

Figure 3. Definition of Thermal Resistance

maximum temperature of 50 °C. For boiling concepts in this case, FC-87 is assumed as the coolant because it has a normal boiling point of 30 °C.

3.2.5 __Coolant Supply Temperature__ - Coolant supply temperatures of 0 °C or greater were desired in order to minimize penalties to the aircraft environmental control system.

3.3 Cooling Concepts

Seven emerging cooling technologies were evaluated. Operating principles, databases, and predicted performances in an avionics cooling application are discussed below. It is assumed that these concepts, despite requiring liquid coolant, can be used by board-mounted electronics. The liquid flow-through board developed under the Air Force PAVE PACE program has demonstrated the practicality of introducing coolant into circuit boards. This board, shown in Fig. 4, uses quick-disconnect fittings to allow easy installation and detachment of the board to and from the chassis. The PAVE PACE board is not capable of 100 W/cm^2 heat removal, but it does pave the way for the utilization of other concepts employing liquid coolant.

3.3.1 __Compact High Intensity Cooler (CHIC)__

The CHIC device was first introduced by Sundstrand in 1983 (Bland, et al. [18]). This liquid single phase cooler combines the thermal efficiency of multiple jet impingement with a large fin area to produce a high effective heat transfer coefficient. Fig. 5 shows the basic elements of a CHIC device. Various laminae are fabricated separately, then stacked and bonded together to form a single cooler element.

The arrows in Fig. 5 show the direction of coolant flow. Entering the inlet port in the end cover, the liquid is pumped through the feed manifold and to the jet orifice plate. This plate usually contains about 50 to 200 small circular holes. The liquid impinges on the target plate, and then is directed back to the drain manifold and ultimately to the exit port. The electronics device is attached to the opposite side of the target plate. Fig. 5 shows a single orifice plate and spacer. Usually the orifice

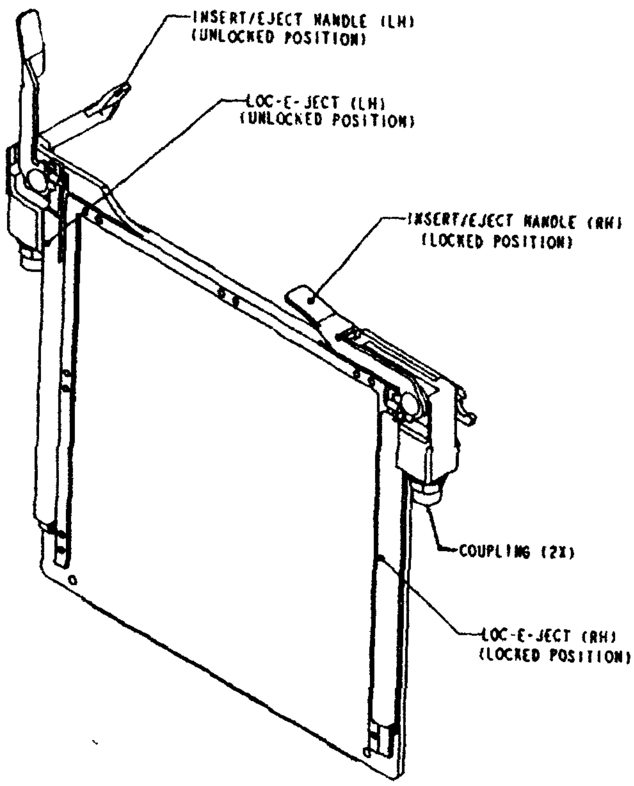

Figure 4. Air Force PAVE PACE Liquid Flow-Through Board

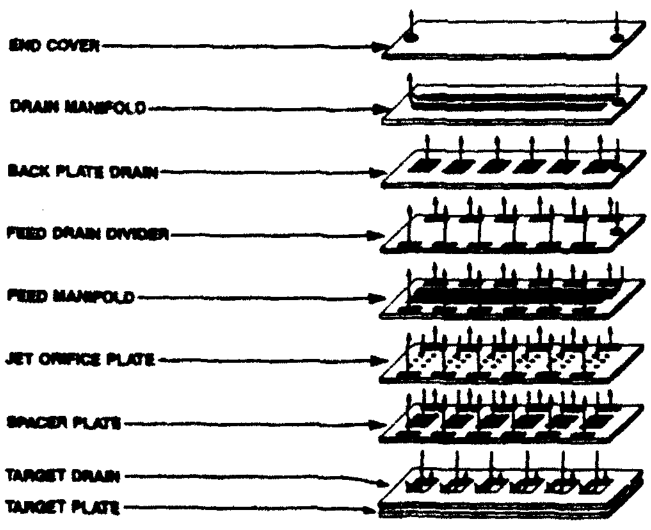

Figure 5. CHIC Elements and Fluid Flowpaths

plate and spacer are repeated several times, with each successive orifice plate acting as a target for the jets from the orifice plate immediately upstream. The orifices are offset by one-half their pitch from plate to plate, so that the liquid impinges on solid metal, then cascades downward as it passes through subsequent orifice plates. The greater the number of plates, the greater the fin effect and thus the higher the effective heat transfer coefficient. The penalty for a large number of orifice plates is higher pressure drop and a thicker heat exchanger.

Database - The original 1983 copper CHIC had a thermal resistance, R-wf, as low as 0.12 $^oC/(W/cm^2)$ at a flowrate of about 70 kg/hr using Freon-11. This device had seven copper orifice plates. The predicted thermal resistance R-wf using PAO in this device for a flowrate of 35 kg/hr is also 0.12 $^oC/(W/cm^2)$.

Recently, multiple CHICs in a single board have been built by Sundstrand. The laminae are photoetched, then stacked and bonded. Diffusion bonding has been demonstrated for copper boards and vacuum brazing for aluminum boards, although the copper technology is further developed. The photoetching process allows virtually anything that can be drawn to be fabricated, so that the designer has liberty in laying out the locations and sizes of the various CHICs on the board.

Since the 1983 prototype, several versions of the CHIC have been built from copper and aluminum. References [11], and [18] through [20], provide heat flux and thermal resistance measurements on a variety of CHIC devices tested with water, Freon-11, and Freon-113. Using much of this data, Sundstrand has developed a validated analytical model to predict the thermal and hydraulic performance of arbitrary CHIC configurations. Since CHIC coolers have not yet been tested with PAO, the Sundstrand model was used for predicting performance, which is given below.

Predicted Performance - A copper CHIC employing seven layers of orifice plates, with a total thickness of about 0.5 cm, was selected to meet the thermal requirements of Section 3.2.2. The design point and performance that were predicted are shown in Table 3, along with those of the other six concepts which were evaluated.

Assessment - Advantages of the CHIC include its apparent capability to use PAO, low flowrate requirement, and proven manufacturing process which is flexible to design changes. Thermal performance is predicted to be excellent using PAO, although the CHIC has not yet been tested with the coolant. Thermal expansion mismatch with the chip must also be considered in the design of copper or aluminum CHICs.

The small orifice diameters required to obtain performance demand attention be paid to the potential for clogging. The minimum diameter orifice usually considered is 127 microns (0.005 in).

The high viscocity of PAO at low temperature calls attention to cold start issues, as mentioned in Section 3.2.1. The room temperature design pressure drop through the CHIC board, not including quick-disconnect pressure drop, and assuming four CHICs operating in series, and a flowrate per series of CHICs of 35 kg/hr, is 140 kPa (20 psi). A supply/return line pressure drop of 35 kPa (5 psi) is assumed, thus resulting in a 175 kPa (25 psi) loop pressure drop, if other components such as filters are neglected. Of

Table 3

Predicted Design Points and Performance *

Concept Design Point					Thermal Resistance ($^{o}C/W/cm^2$)			
Cooling Concept	Coolant	Coolant Flowrate (kg/hr)**	ΔP (atm)	Coolant Supply Temp. (^{o}C)	R-jc	R-cw	R-wf	R-tot
CHIC	PAO	20	1	37	0.20	0.20	0.13	0.53
Curved Surface	FC-87	480	1	0	0.20	0.20	0.35	0.75
Evaporative Spray	FC-72	35	2	36	0.20	0.00	0.16	0.36
Heat Pipe	Water	N/A***	N/A	37	0.20	0.20	0.12	0.52
Jet Impingement-Bare Chip	FC-72	70-280	1	16	0.20	0.00	0.49	0.69
Jet Impingement-Enhanced Surface	FC-87	25-100	1	10	0.20	0.20	0.28	0.68
Microchannel	PAO	35	5	0	0.20	0.20	0.50	0.90
Pumped Capillary Evaporator	Ammonia	N/E	N/E	N/E	0.20	0.20	0.15	0.55

* These values are extrapolated from test data, conditions, and coolants which are often different from the identified design points.

** Based on 1.0 cm^2 chip dissipating 100 W heat flux.

*** Also requires PAO flow loop for heat sink.

N/E = Not Evaluated

the 140 kPa pressure drop in the CHICs, 99 kPa is incurred through the orifices, and 41 kPa through the internal manifolding. For laminar flow, the manifold pressure drop is proportional to dynamic viscosity. However, orifice pressure drop is proportional to jet velocity squared and independent of viscosity. Therefore, a substantial portion of the pressure drop is unaffected by fluid viscosity. Calculations at -40 °C indicate that a flowrate of 4 kg/hr (11% of the room temperature value) is obtainable for a loop total pressure drop of 280 kPa (40 psi); 10 kg/hr (29% of the room temperature value) can be provided for a pressure drop of 700 kPa (100 psi). While these flowrates are well below the design flowrates necessary to cool 100 W/cm^2 heat-dissipating chips, they appear sufficient to initiate coolant movement and allow for the system to begin to warm up.

3.3.2 Curved Channel Flow with Subcooled Boiling

This concept employs turbulent flow and bouyancy forces to assist the boiling process. As shown in Fig. 6, the heat source is mounted on the concave side of a curved flow channel. A subcooled liquid flowing through the channel experiences nucleate boiling as it passes over the heat source. Since the bubbles are less dense than the surrounding liquid medium, the induced radial acceleration drives the bubbles from the surface. Bubble removal is also enhanced by shear forces in the

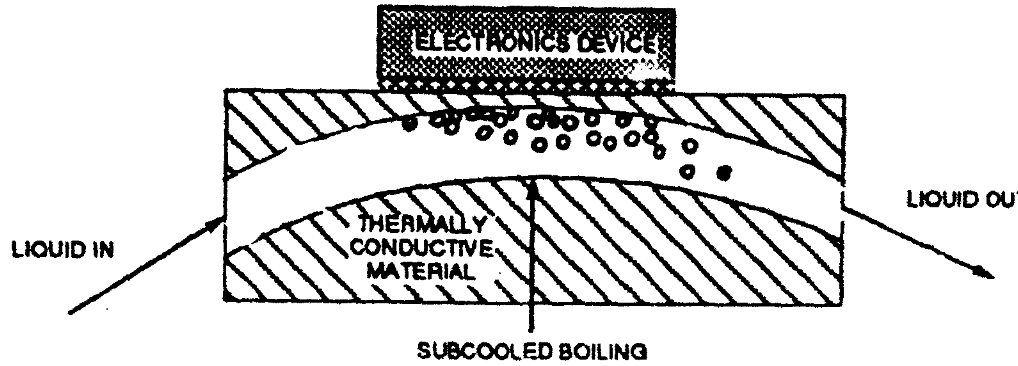

Figure 6. Curved Channel Flow with Subcooled Boiling

turbulent flow. Secondary flow resulting from the curved flowpath may also affect bubble rem[illegible]. The efficient bubble removal process increases heat transfer coefficient a[illegible] forestalls boiling burnout. High radial forces can be created with even moderate flowrates. For example, with a 2.54 cm radius of curvature, a flow velocity of 5 m/s will induce a 100 g radial acceleration.

Fig. 6 depicts an electronics device mounted outside the flowpath in order to provide a smooth flow channel. Gu, et al. [21] found that nonflush mounting of heat sources inside the flow channel leads to significantly reduced values of critical heat flux (CHF).

Database - Research into augmenting the boiling process with induced accelerations dates back to the 1950s, and includes such cooling applications as rocket motor cases, space-based cooling in the absence of gravity, and the need to understand the effects of acceleration on boiling (see, e.g., [22] through [28]). These investigations established a correlation that CHF is proportional to the fourth root of acceleration for acceleration levels over 10 "g's." More recently, Leslie, et al. [29] demonstrated the advantages of replacing linear flow with curved surface flow in order to increase CHF and thereby gain better performance with X-ray sources.

While most of the earlier investigators used water as the coolant, some recent work has been done using coolants with lower freezing and boiling points. Gu, et al. [21] tested subcooled boiling of FC-72 in both straight and curved channels. Their results show, at a flow velocity of 4 m/s, about a 45% increase in CHF using a curved channel as compared to a straight channel. CHF was also found to be sensitive to velocity and the amount of subcooling. In a straight channel, CHF increased by as much as 90% as velocity increased from 1 m/s to 4 m/s. CHF also increased by 50% to 100% when subcooling of the FC-72 was increased from 0.5 ^{o}C to 20 ^{o}C. Thus, radial acceleration did not appear to be the greatest driver in establishing CHF.

Using FC-72, Leland and Chow [30] found that channel curvature had only a weak effect on CHF. They report that any enhancement in CHF due to channel curvature diminishes as subcooling increases.

Predicted Performance - The heat flux data published by Gu, et al. [21] using FC-72 was used to predict performance. Their data indicate that substantial subcooling and high velocity flow are needed to meet the F.O.S. requirement on heat flux stated in Section 3.2.2. The design point and predicted performance are shown in Table 3.

Data from Leland and Chow [30] suggest that channel height must be at least 1 mm to preclude CHF degradation. Given this minimum height, a 1-cm channel width (to match the nominal chip width), and a requisite 8 m/s flow velocity in order to meet F.O.S. requirements, the design flowrate is 480 kg/hr.

Assessment - An advantage of this concept is its simplicity. Fabrication should be relatively inexpensive. Because the liquid is subcooled, there is no need for a condenser, and the flow loop resembles that of a single phase cooler. The concept has several disadvantages, the most important being that a significant benefit obtained by inducing radial accelerations has not yet been clearly established for heat flux levels and coolants which are applicable to electronics cooling.

3.3.3 Evaporative Spray Cooler

Evaporative spray cooling makes use of the low thermal resistance obtainable through the evaporation process while minimizing flowrate requirement. As depicted in Fig. 7, a pressurized, subcooled liquid is forced through a nozzle, atomized, and the resultant droplets impinge upon the heated surface. Under optimum operating conditions, approximately 20% to 30% of the liquid is vaporized upon impinging. This is a much greater percentage than for subcooled boiling, so the required flowrate is lower.

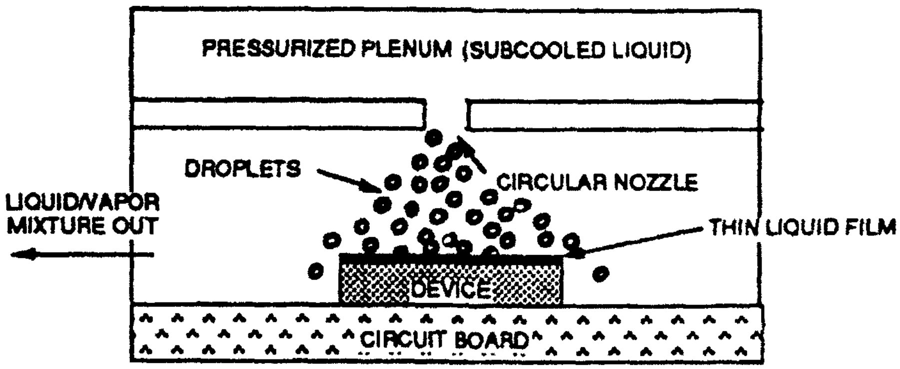

Figure 7. Evaporative Spray Cooling.

One of the purposes of cooling in the form of a spray is to forestall the dryout of the heated surface which results from film boiling. Given a sufficiently high impingement velocity, it is believed that the droplets can, up to a point, penetrate the developing vapor film on the surface of the chip and delay surface dryout, thereby raising CHF.

Database - References [31] through [34] describe earlier work in this field. Water was used as the working fluid, and heat fluxes as high as 2000 W/cm^2 (at a surface superheat of 200 ^{o}C) proved that evaporative spray was a viable high flux cooling technique. Tilton, et al. [35] summarized these earlier efforts and concluded that the heat fluxes obtained from them varied considerably due to the sensitivity of thermal performance to spray conditions. Consequently, parametric testing was performed to understand the influence of spray conditions on thermal performance, which is documented in references [36] through [40]. Tests have recently been performed using the dielectric coolant FC-72, with a maximum CHF obtained of about 300 W/cm^2 [41]. The latest versions of this cooler are about 1 cm thick.

Predicted Performance - The reference [41] data on FC-72 was used to predict design operating conditions to meet the requirements in Section 3.2.2. The design point and predicted performance are shown in Table 3. For all actively pumped two-phase concepts, the coolant was assumed to be subcooled by 20 ^oC to preclude pump cavitation; this is reflected in the coolant supply temperature shown.

Assessment - Advantages of evaporative spray cooling include high heat flux capability and low thermal resistance between the coolant and the device. The total thermal resistance from device junction to coolant is the lowest of the concepts studied. Flowrate requirements are also low. A substantial database with parametric variations has been amassed. Finally, redundancy is offered by using multiple nozzles per chip.

A potential disadvantage of this concept is that, being a two-phase system, the cooling cycle is more complex than that of a single phase system. In an accelerating system such as a fighter aircraft, vapor collection and condensation present challenges. Using a dielectric refrigerant such as FC-72 or FC-87 would require stocking an additional coolant, thus impacting maintainability costs.

The high impingement velocity (~20 m/s or more) calls attention to chip integrity. Tests have been conducted only on copper heaters, so data is unavailable to determine whether or not erosion would be a problem. If it is, then the device could be protected by bonding a shield or applying a conformal coating..

3.3.4 Heat Pipe

The operation of heat pipes is well documented (see, e.g., Skrabek [42]). The pipe is lined with a wicking material which in turn is saturated with a liquid working fluid. The liquid is evaporated at the heated end of the pipe, and the resulting pressure increase drives the vapor toward the opposite end, where the vapor rejects heat to a heat sink and condenses. The condensate is then pulled by capillary force back to the evaporator end to complete the cycle.

Database - Much work has gone into developing heat pipes for cooling avionics, and heat pipe cold planes have entered military air vehicle operation. Heat pipes are used for cooling discrete electronics on printed wiring boards on the ERIS missile optical seeker, as well as the LANTIRN targeting and navigation pods for the F-18. Both of these heat pipes are of copper construction, have a sintered powder copper wick construction, and employ water as the working fluid. These heat pipes have passed environmental testing including storage to -54 ^oC. The sintered wick structure seems to allow the water to freeze without damaging the heat pipe. Both these applications have low local heat flux capabilities compared to the requirements of this study.

An advanced heat pipe heat spreader [43] for cooling high power devices has been built and tested to over 100 W/cm^2 with methanol, and to over 200 W/cm^2 with water [44]. This device, depicted in Fig. 8, uses vapor chambers to spread the vapor over an area much larger than the area of the heat source. The condenser, which is slightly

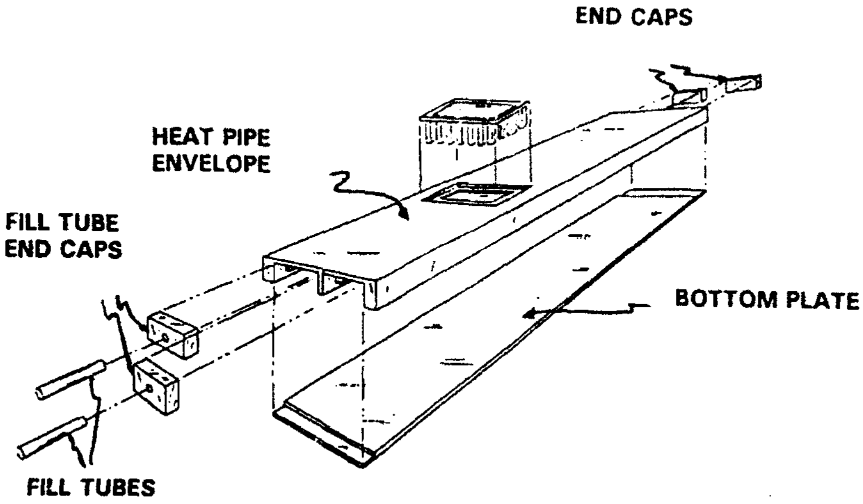

Figure 8. Exploded View of Heat Pipe Heat Spreader

smaller than the area of the bottom plate, therefore incurs a small ΔT. This design also employs copper posts beneath the heat source to increase heat transfer area at the evaporator end. The two vapor chambers shown contain wick material for recirculation of the fluid. The cooler tested was 1.27 cm thick but was not designed for minimum thickness; thinner versions appear possible while still meeting heat flux requirements.

Thermal resistance between the copper shell and vapor (i.e., R-wf) was measured to be 0.38 $^{o}C/(W/cm^2)$ using methanol, and 0.12 $^{o}C/(W/cm^2)$ using water. Assuming that the shell temperature is at 50 ^{o}C (see Section 3.2.4), then at a heat flux of 100 W/cm^2, with water as the working fluid, the vapor temperature is equal to 38 °C. At such a low vapor temperature, the vapor pressure of the water in the heat pipe is about 1/16th atmosphere. Operating at much lower pressures could incur serious performance penalties.

A relatively significant thermal resistance in the path from device junction to ultimate heat sink for a heat pipe can be that due to clamping the electronics board to a chassis. The condenser end of the heat pipe usually rejects heat to an air- or liquid-cooled chassis through a clamping mechanism. The PAVE PACE flow-through board now makes it possible to bring a liquid heat sink onto the board, thereby eliminating the clamping thermal resistance. It would appear straightforward to adapt the flow-through board to allow the liquid to serve as a condenser heat sink for heat pipes. It is thus assumed that clamping thermal resistance can be eliminated for an advanced heat pipe.

Predicted Performance - The data on the heat pipe heat spreader were used to arrive at the design point shown in Table 3.

The high forces of acceleration experienced in a fighter aircraft were of concern in evaluating heat pipes. The smallest peak acceleration levels, usually felt along the lateral axis of the aircraft, are typically about 2 g's. Even if heat pipes were oriented along this axis, a 2-g acceleration is great enough to significantly degrade the heat pipe performance. A similar conclusion was also reached by Beam [45]. This problem might be overcome by limiting the length of the heat pipes in order to minimize capillary pumping distance.

Assessment - Advantages of the heat pipe heat spreader include its relative simplicity and low weight. A disadvantage is performance degradation under high acceleration levels. Because this concept employs heat spreading, it is better suited for singular or relatively widely spaced electronics devices than for devices mounted in compact arrays. Since water is required as the coolant to obtain the required thermal performance, start-up performance from a cold start condition must be determined.

3.3.5 Jet Impingement with Subcooled Boiling

This concept utilizes both high single-phase heat transfer and boiling. A subcooled liquid is forced through a nozzle. Single or multiple nozzles may be used, and they may be circular or slotted. Fig. 9 depicts the configuration selected for evaluation, which uses a single slotted nozzle. Subcooled boiling augments the single-phase heat removal, and is enhanced by shear forces from the turbulent flow.

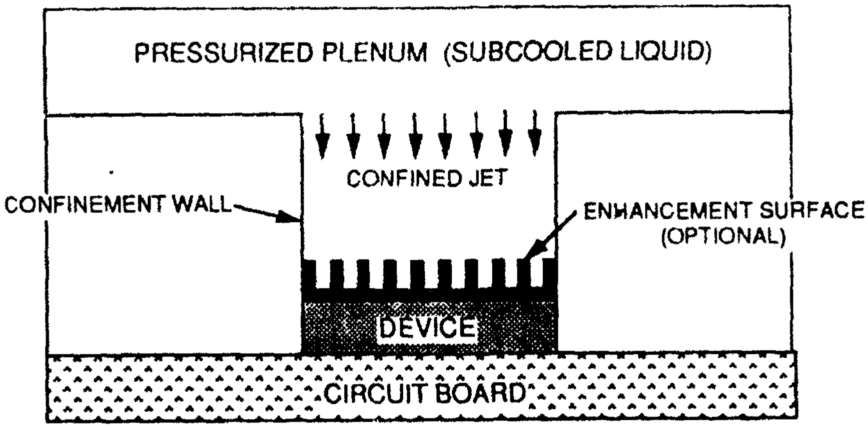

Figure 9. Jet Impingement With Subcooled Boiling.
This configuration uses a slotted nozzle of very narrow width and extending the length of the device to produce a linear jet as shown. After impinging on the device or enhancement surface, the liquid turns 90 degrees and exits, still in the subcooled state, "into and out of the page" relative to the drawing.

Two variations of this concept were evaluated: one where the bare chip is cooled directly by the jet, and the other where a finned surface (called an enhancement surface) is bonded to the chip. In both cases, the electronics board is immersed in a dielectric coolant. Bare chip cooling often provides the lower thermal resistance by bringing the coolant into direct contact with the chip. Surface enhancement, on the other hand, provides higher heat flux capability.

Database - Jet impingement boiling for the purpose of cooling electronics has received considerable attention recently. Ma and Bergles [46] provide an overview of the work performed through 1982, and provide boiling data for circular submerged jets of R-113. CHFs of up to 100 W/cm^2 were obtained. Jaeger, et al. [47] present data for single and multiple circular jets of saturated Freon-12 impinging upon a silicon heat source. The greatest value of CHF, 200 W/cm^2, was obtained when flowrate and jet velocity were both maximum. Nonn, et al. [48] also show data for single and multiple jets. The maximum value of CHF for an FC-72/FC-87 mixture was approximately 100 W/cm^2, and occurred at maximum subcooling (41 ^{o}C), maximum jet velocity (6.36 m/s), and maximum number of jets (nine).

Wadsworth and Mudawar [49] describe the use of a single slotted nozzle to provide cooling uniformity and high heat flux. Their results are for single-phase flow, but they extend their work to subcooled boiling [50]. CHFs of up to 411 W/cm^2 were obtained using FC-72 and microgroove surface enhancement. Effects of surface enhancement are discussed in [51], [52], and [53].

Predicted Performance - The ref. [50] data, obtained using rectangular nozzles and FC-72 coolant, were used to size this concept. Maximum CHFs were reported at a jet velocity of 12.9 m/s and a subcooling of 40 ^{o}C, and were 249 W/cm^2 for a smooth surface and 411 W/cm^2 for microgrooved enhanced surface. Smooth surface data were assumed applicable to a bare chip, while the data with microgroove surface enhancement were directly applicable to a chip with an enhancement surface bonded to it. The operating conditions needed to meet the requirements of Section 3.2.2 are shown in Table 3.

For all actively pumped two-phase concepts, the coolant was assumed to be subcooled by 20 ^{o}C to preclude pump cavitation; this is reflected in the coolant supply temperature shown in Table 3 for the enhanced surface variant. The bare surface variant required 40 ^{o}C subcooling in order to meet the required thermal performance.

Assessment - Advantages of boiling jet impingement include a strong thermodynamic database and proven feasibility. This concept is currently used in industry to test some high power devices. Its simplicity lends itself to standard manufacturing techniques such as milling or stamping. The slotted nozzles tested have shown themselves to be free from clogging over long operating periods. Slotted nozzles seem to be less susceptible to clogging than circular nozzles. Because the refrigerant is subcooled, the flow loop resembles that of a single phase system, so no condenser is required. The steepness of the boiling curve at higher heat fluxes adds stability to the chip temperature should excursions from the design heat flux occur. The bare chip variant eliminates the uncertainty associated with contact conductance between the chip and intermediate surface.

Flowrate requirement will depend upon the minimum nozzle width acceptable to provide adequate cooling and to avoid clogging. The ranges of flowrate shown in Table 3 are based on the range of nozzle widths tested. Like the other boiling concepts studied, this concept requires stocking an additional coolant for the aircraft, thus impacting maintainability costs.

Finally, thermal performance data were based on an 8-cm-thick cooler not designed for minimum thickness. There are no foreseeable obstacles to reducing this thickness significantly while maintaining thermal performance, but this must be verified through experiment. Nozzle-to-impingement surface standoff distance has been tested from 0.05 cm to 0.5 cm, with little effect on thermal performance [54].

3.3.6 Microchannel Cooler

Conventional microchannel coolers, first introduced by Tuckerman and Pease [55], are liquid single phase heat exchangers that operate in the laminar flow regime. Despite these two thermally undesirable characteristics, microchannels provide high heat removal by exploiting two features: high aspect ratio flow passages and large fin area. Nusselt number for fully developed laminar flow in rectangular passages is known to increase with passage aspect ratio. A 10:1 aspect ratio channel gives a Nusselt number about double that of a square channel. A typical microchannel cooler is shown in Fig. 10. The narrower the channels, the greater the fin area, and the higher the effective heat transfer coefficient. A drawback to using narrow channels is high pressure drop. Increasing channel depth has beneficial results both in terms of heat transfer effectiveness and in pressure drop. Deeper channels provide greater fin area, thus permitting a lower flow velocity for a given mass flowrate, which in turn leads to a lower pressure drop.

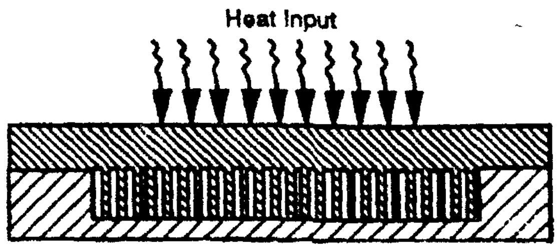

Figure 10. Microchannel Cooler

Database - A large percentage of the work done on microchannels has dealt with etching them into silicon [55], [56], [57]. Much progress has also been made on metallic and ceramic microchannels, mostly for the purpose of cooling laser diodes [58], [59], [60], [61]. A listing of microchannel designs, operating conditions, and thermal performances from several sources is provided by Phillips [62].

The experiments performed to date have generally used water as the coolant. Therefore, the heat fluxes found in most of the prior investigations are higher than what would have been obtained using an aircraft-compatible coolant such as PAO. On the other hand, many previous microchannels were significantly limited in thickness in order to meet the constraints imposed by laser diode applications. Heat flux capability is sensitive to microchannel thickness, and increases substantially as the thickness increases. The thickness requirement imposed by avionics cooling applications is not as severe as for laser applications; therefore, thicker microchannels can help offset the negative effects of using a thermally poorer coolant than water.

Manufacturing efforts to date have stressed single microchannels dedicated to cooling single heat sources - usually on the order of one square centimeter footprint. To enable cooling multiple chips mounted on a board, current manufacturing processes would require tying together many individual microchannels. This may be compared to CHIC manufacturing processes where an entire board containing multiple CHICs can be fabricated as a single unit. No similar multicooler fabrication technique for microchannels could be found in this study.

Predicted Performance - Microchannels embedded within silicon devices offer the lowest thermal resistance, but they require altering the device. A cooler was sought which was separate from the electronics devices. Therefore, copper and aluminum microchannels were studied. They are nonintegral and have high thermal conductivity. Thermal analysis was performed using equations for microchannel thermal and hydraulic performance from Phillips [62]. Assumptions included PAO coolant, an allowable 5 ^{o}C bulk temperature rise across the device, and a flow length of one cm. Channel width was assumed to be 0.127 mm and the height 0.635 mm, based on current machining processes. An analysis program was written and calibrated for thermal resistance and pressure drop with published water test data. The design point and predicted performance using this analysis program are shown in Table 3. The total thickness of this design is approximately 1 mm.

Assessment - Advantages of microchannels include high heat flux capability, low thermal resistance, presumed compatibility with PAO, and thinness. Disadvantages include high pressure drop and a required low coolant supply temperature for the cooling requirements of this program. No method of fabricating multiple microchannel boards, similar to the multiple CHIC boards described earlier, was found while conducting this study. Complex plumbing would be required to cool multiple sites with an arbitrary layout. Additional potential disadvantages include clogging of the narrow coolant passages, and cooling delay during cold start due to the high viscosity of PAO combined with the inherently high pressure drop of microchannels.

Microchannel performance could be improved significantly by switching to ethelyne-glycol/water (EGW) or by constructing deeper channels. With EGW, thermal performance approximately doubles and pressure drop is reduced compared with PAO. Corrosiveness and electrical hazards, however, would be a concern. Development of manufacturing methods to produce deep, thin channels in copper or aluminum is also a means of providing improved performance.

3.3.7 Pumped Capillary Evaporator

This device, depicted in Fig. 11, resembles a heat pipe, but uses a pump to supplement liquid transport. The pressure head generated by the pump pushes the liquid through a distribution network and through the capillary medium where a portion of the liquid is vaporized. Pumping pressure can easily overcome the acceleration forces of flight, which can limit performance of conventional capillary pumped heat pipes. Active pumping also provides higher flowrates than heat pipes, which results in superior thermal performance.

Database - Because this system contains a central core for liquid distribution, water, upon freezing, would crack the structure. Therefore, this system cannot use water as does the heat pipe, and has consequently been developed using ammonia, methanol, and methylamine [63]. With ammonia, which is the best thermal performer of the three, the shell-to-vapor thermal resistance (R-wf) has been measured as low as 0.15 ^{o}C/(W/cm^2), and heat fluxes have been measured exceeding 250 W/cm^2 [44]. The thickness of these coolers ranges from about 0.3 to 0.6 cm.

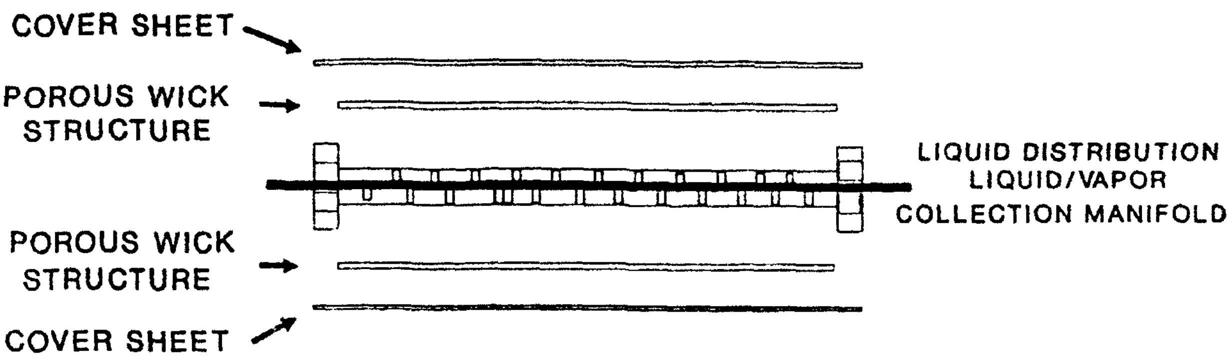

Figure 11. Actively Pumped Capillary Evaporator (Exploded View)

Predicted Performance - The predicted design point and thermal performance using ammonia are shown in Table 3.

Assessment - Advantages of the actively pumped capillary evaporator include high demonstrated heat flux and low thermal resistance. Its greatest disadvantage in its present state of development is its reliance on a toxic, corrosive, or flammable coolant. Conversion to a more benign coolant would be required to make this concept more viable.

3.3.8 Other Concepts - Several other concepts were studied but were not pursued in detail because they were assessed as not capable of meeting the 100 W/cm^2 heat flux requirement. The PAVE PACE flow-through board, illustrated in Figure 4, is limited to about 10-20 W/cm^2 heat flux when junction temperature must be maintained at 90 °C. Thermoelectric coolers likewise are limited to about the same heat flux level. A cooling concept receiving recent attention is microencapsulated phase change material (PCM) introduced into a coolant such as PAO to form a slurry [64]. The PCM, which can be a paraffin or other material with suitable melting temperature, is encapsulated in a protective shell such as a polymer. The latent heat that the PCM provides raises the effective heat capacity of the liquid significantly. The thermal benefit is felt mainly in terms of reduced flowrate requirement, not in increased heat flux capability.

3.4 Concept Comparisons

Table 4 presents the results of the trade study in summary form. Each of the concepts evaluated in detail is rated against the evaluation criteria which were identified in Section 3.1.1. For each criterion, two scores are provided: a raw score from 1 to 3, 3 being the best; and a weighted score, which is the raw score multipled by the weighting factor assigned to the particular criterion. Discussions of the scores assigned, by criterion, are provided in the following paragraphs.

Table 4

Trade Study Scoring Results

		COOLING CONCEPT Raw Score * / Weighted Score							
CRITERION	Weighting Factor	*CHIC*	Jet - Enhanced Surface	Evap. Spray	Heat Pipe	Jet - Bare Surface	Micro-channel	Curved Channel	Pumped Capillary Evap.
Weight Impact	15	3 / 45	2 / 30	3 / 45	3 / 45	1 / 15	1 / 15	1 / 15	2 / 30
Life Cycle Cost	15	2 / 30	2 / 30	2 / 30	2 / 30	2 / 30	2 / 30	2 / 30	2 / 30
Safety	15	3 / 45	3 / 45	3 / 45	3 / 45	3 / 45	3 / 45	3 / 45	1 / 15
Reliability	15	3 / 45	3 / 45	2 / 30	2 / 30	3 / 45	3 / 45	3 / 45	1 / 15
Mfg. Status	10	3 / 30	2 / 20	1 / 10	2 / 20	2 / 20	2 / 20	1 / 10	3 / 30
Testing Status	10	3 / 30	3 / 30	3 / 30	3 / 30	3 / 30	2 / 20	2 / 20	3 / 30
Thickness	8	3 / 24	2 / 16	3 / 24	3 / 24	2 / 16	3 / 24	2 / 16	3 / 24
Lateral Size	8	3 / 24	3 / 24	3 / 24	1 / 8	3 / 24	3 / 24	3 / 24	3 / 24
Life	2	2 / 4	2 / 4	2 / 4	2 / 4	2 / 4	2 / 4	2 / 4	2 / 4
Flexibility and Growth	2	3 / 6	3 / 6	3 / 6	3 / 6	3 / 6	3 / 6	2 / 4	3 / 6
Total Wtd. Score	**100**	**283**	**250**	**248**	**242**	**235**	**233**	**213**	**208**

*** Raw Score: 1 = Poor 2 = Fair 3 = Good**

It would seem desirable to compare the maximum heat flux capability or minimum thermal resistance offered by the concepts. To make a fair comparison, however, is impossible without imposing equal constraints upon each concept. Each concept could realize significant performance improvement by using exorbitant flowrate, fin area, thickness, or pressure drop. The approach taken here is to compare these operating parameters given equal thermal performance requirements, and, thereby, indirectly evaluate thermal performance. The effect of thermal performance on these parameters is manifested under "System Weight Impact" discussed in the following section.

3.4.1 System Weight Impact - If total heat load is large, then the heat exchanger operating conditions will have a discernible impact upon aircraft take-off gross weight (TOGW). TOGW increases when a high coolant flowrate or a low coolant supply temperature is required. The weight of the heat exchanger and its operational pressure drop also impact TOGW, though to a lesser degree. Examination of Table 3 shows that the CHIC and evaporative spray cooler impose the least demands on flowrate and coolant supply temperature.

The sensitivity of fighter aircraft TOGW to HFHE operating parameters was estimated for the case of PAO as coolant. An advanced fighter in its baseline mission role was used for the analysis. A vapor cycle system was assumed as the intermediate cooling loop for transporting heat from the HFHE loop to the aircraft fuel heat sink. The analysis was performed using the McDonnell Douglas Computer-Aided Environmental Control System (CAECS) software. CAECS, an enhanced version of the Wright Laboratory AECS software, computes steady-state flow rate, pressure drop, temperature, and enthalpy at each location in the system. It then computes component weight and power requirements based upon flow conditions. TOGW penalty is calulated by multiplying applicable penalty factors (for a representative advanced fighter aircraft) by weight, power, and ram air flowrate from CAECS.

The calculated sensitivities of TOGW to coolant flowrate, pressure drop, supply temperature, and fixed weight of the HFHE, are shown in Figures 12 through 15, for the case of a 2 kW total heat load. The results are expressed in terms of ΔTOGW from an assumed baseline condition. The results indicate that TOGW is most sensitive to coolant supply temperature and coolant flowrate, and less sensitive to HFHE weight and pressure drop.

The predicted design operating points presented in Table 3 may be used to determine relative impact on TOGW of HFHE concepts employing PAO. Because the flowrates given in Table 3 are based upon a 100 W heat load, they must be multiplied by 20 before being applied to Figure 13, which is for a 2 kW heat load. As an example of TOGW sensitivity, for a 2 kW total heat load, TOGW is predicted to be 14 kg (31 lb) higher when employing the microchannel than when employing the CHIC. At higher total heat loads, this difference would of course be greater. For this assessment, the weight of the CHIC and microchannel heat exchangers were not used due to lack of information. Fig. 15, however, indicates that heat exchanger weight will have a relatively small impact on TOGW.

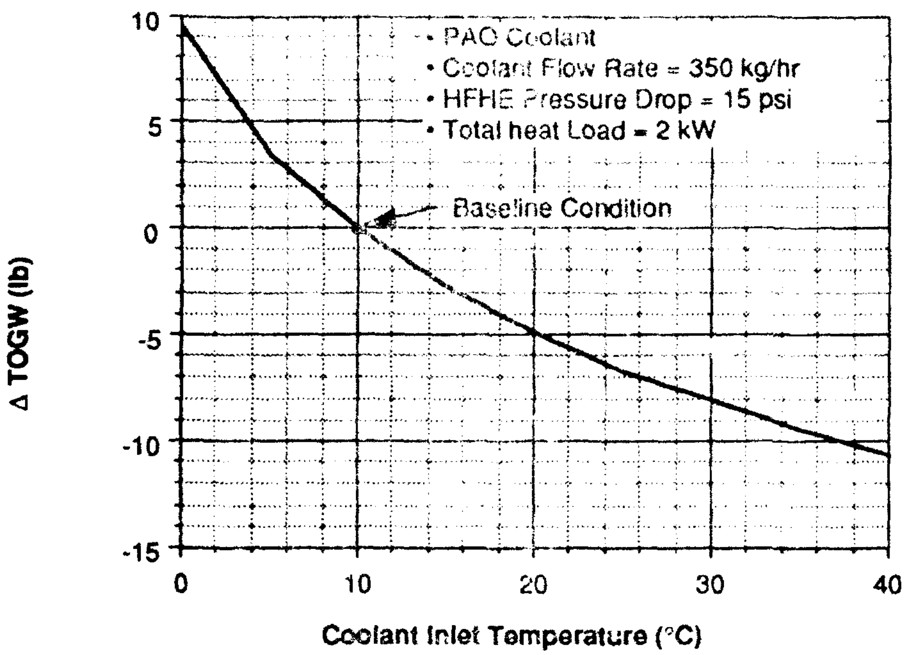

Figure 12. Sensitivity of Aircraft Take-Off Gross Weight to Coolant Supply Temperature.

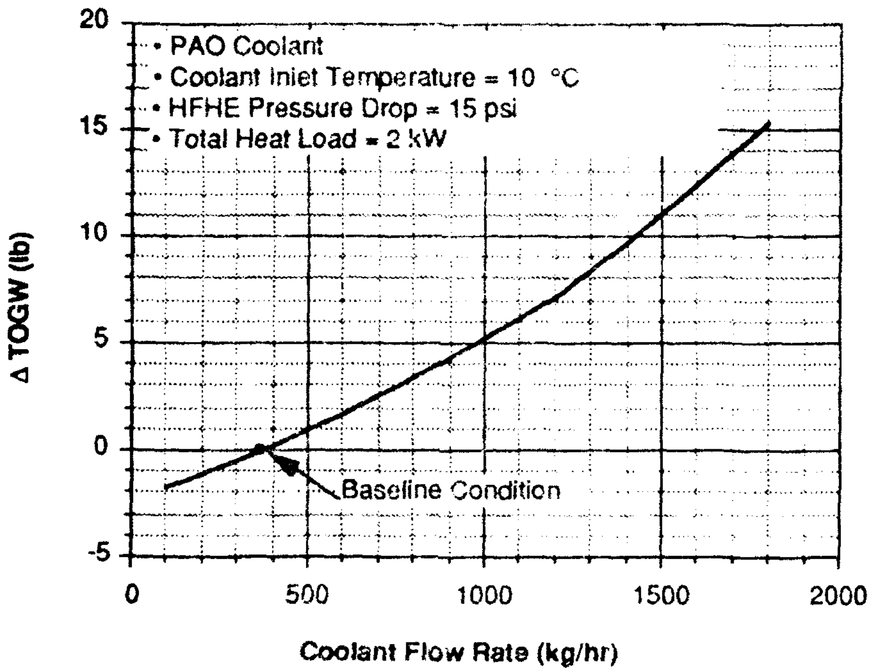

Figure 13. Sensitivity of Aircraft Take-Off Gross Weight to Coolant Flowrate.

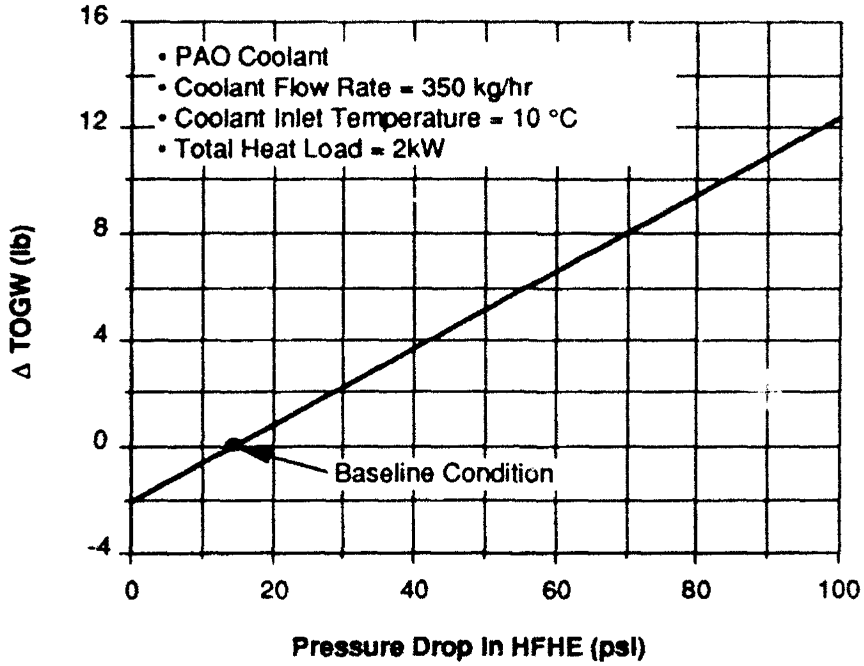

Figure 14. Sensitivity of Aircraft Take-Off Gross Weight to HFHE Pressure Drop.

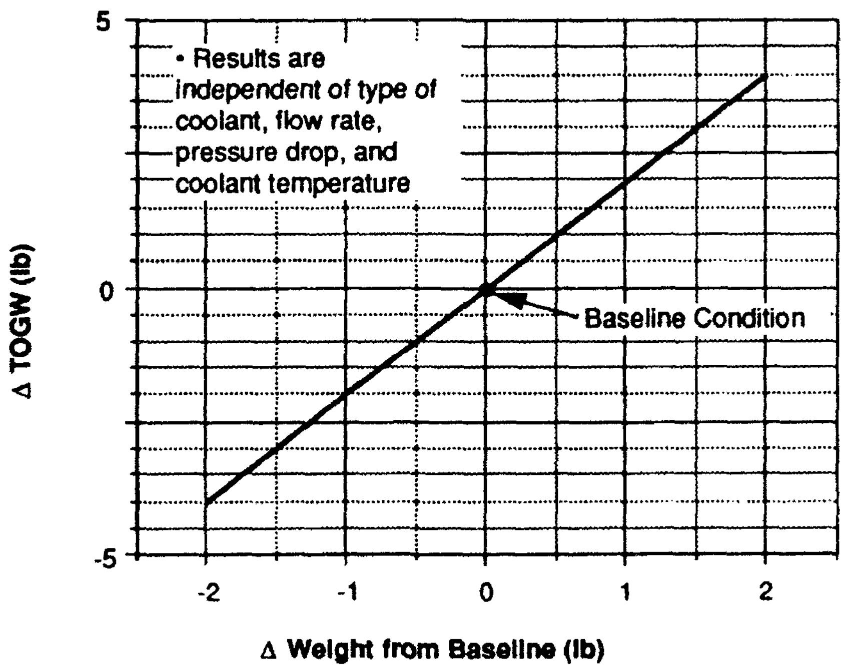

Figure 15. Sensitivity of Aircraft Take-Off Gross Weight to HFHE Structural and Contained Coolant Weight.

3.4.2 Life Cycle Cost

A qualitative, comparative assessment of life cycle cost (LCC) was made. It is recognized that the accuracy of an LCC estimate is limited to the extent of concept development discussed in Section 3.4.4. For example, concepts lagging in manufacturing status often *appear* to be less complex (and thus less costly) than concepts which are further developed.

The LCC analysis, shown in Table 5, is broken into three categories: development cost, manufacturing cost, and maintenance cost. Development cost ratings are based directly on development status ratings (see Table 7). Manufacturing cost ratings include considerations such as complexity, number of parts, material, tolerances, and manufacturing processes. Maintenance cost ratings are based on complexity and system impact. An important system impact is the choice of coolant. Since future fighter aircraft will use PAO, the CHIC and microchannel cooler, if employing PAO, reduce maintainability cost in this regard. Concepts requiring the use of another coolant will require the stocking of this coolant and thus will increase maintainability costs.

The column designated "average rating" was rounded to the nearest whole number for use in the Table 4 Trade Study Scoring Results.

Table 5

Life Cycle Cost Assessments

CONCEPT	Development Cost	Manufacturing Cost	Maintenance Cost	Average Rating
CHIC	3	2	2	2.3
Curved Channel	1	3	2	2.0
Evaporative Spray	2	2	1	1.7
Heat Pipe	2	2	3	2.3
Jet Impingement (both variants)	2	2	2	2.0
Microchannel	2	1	2	1.7
Pumped Capillary Evaporator	3	2	1	2.0

Scoring: 1 = Poor 2 = Fair 3 = Good

3.4.3 Safety and Reliability

Reliability ratings of the heat exchangers were made by identifying the number of potential failure modes as well as by assessing complexity. Like LCC ratings, reliability ratings are qualitative and relative. Table 6 shows potential failure modes and complexity factors which entered into the reliability assessment. These were identified by an "X" when they applied to a particular concept. The total number of "X's" were then used to give an overall assessment of reliability.

Table 6

Reliability Assessment

	POTENTIAL FAILURE MODES						COMPLEXITY FACTORS		
CONCEPT	Leakage	Clogging	Contact Conductance	Boiling Instabilities	Pump Cavitation	High g	HFHE Complexity	Cooling Loop Complexity	Total/ Rating*
CHIC	X	X	X				X		4/3
Curved Channel	X		X	X	X				4/3
Spray	X	X		X	X		X	X	6/2
Heat Pipe	X		X	X		X	X		5/2
Jet (enhanced surface)	X		X	X	X				4/3
Jet (bare surface)	X			X	X				3/3
Micro-channel	X	X	X				X		4/3
Pumped Capillary Evaporator	X	X	X	X	X		X	X	7/1

* For "Total/Rating," "Total" refers to the number of "X's" a concept received, and "Rating" refers to the score (1, 2, or 3) given for use in Table 4, the trade study assessment. "Totals" of 3 and 4 yielded a score of "3," 5 and 6 a score of "2," and 7 or higher, a score of "1."

All the concepts employ a liquid coolant and thus are considered susceptible to leaks. Curved channel flow and jet impingement both utilize slotted flow channels which tend to resist clogging. The heat pipe, being a sealed unit with no active pumping, will also resist clogging. The other concepts employ small feature sizes which present clogging potential. All the concepts, with the exception of evaporative spray and the bare surface variant of boiling jet impingement, rely on heat conduction from the electronics device across an interface to the wetted surface. Poor thermal contact, or degradation of contact over time, could lead to electronics failure. Boiling instabilities, which occur near CHF, are further potential causes for failure. The CHIC and microchannel cooler are single phase systems and are thus immune to boiling instabilities. The boiling concepts are also vulnerable to pump cavitation. As mentioned in Section 3.3.4, the heat pipe suffers reduced performance or dryout under high adverse acceleration. The concepts identified as "complex" require the most number of parts and/or the most intricate parts. The heat pipe would require further development to overcome high g-forces, which presumably would lead to increased complexity. The spray cooler and pumped capillary evaporator require a condenser in the coolant loop and are thus considered to entail relatively complex cooling subsystems.

Safety appears to present no problem except for the pumped capillary evaporator, which uses a flammable or toxic coolant.

3.4.4 **Development Status and Risk** - Testing and manufacturing status are included in the tradeoff because they not only impact risk, but they also affect confidence in the thermal performance predictions. Most of the concepts, because they are still being developed, are in some need for further testing or packaging development. Further development might result in improved thermal performance, or, perhaps, uncover unexpected problems which lead to reduced performance.

The development status of the various concepts is compared in Table 7. The status of both manufacturing and testing each concept is rated. Under both these categories, the status is further subdivided into "proposed cooler" and "similar coolers." This subdivision is necessary because some devices, an example being the microchannel cooler, have been extensively developed for other applications, but lag development for high flux avionics cooling applications with multiple heat sources. In the case of the microchannel cooler, the extensive test and manufacturing databases developed for silicon coolers and laser diode applications certainly contribute to reducing the risk in the development of future devices, and thus are accounted for under the column "similar coolers."

The "average scores" shown in Table 7 were rounded to the nearest whole number for use in the Table 4 Trade Study Scoring Results.

Most of the concepts are supported with ample test data. Practical designs and proven manufacturing methods have been demonstrated for the CHIC, microchannel, pumped capillary evaporator, and heat pipe, whereas the other concepts have been mainly built for laboratory thermal performance demonstrations.

Table 7

Development Status Evaluation

	MANUFACTURING			TESTING		
COOLING CONCEPT	Proposed Cooler	Similar Coolers	Avg. Score	Proposed Cooler	Similar Coolers	Avg. Score
CHIC	2	3	2.5	2	3	2.5
CURVED CHANNEL	1	1	1.0	1	2	1.5
EVAPORATIVE SPRAY	1	1	1.0	3	3	3.0
HEAT PIPE	1	3	2.0	2	3	2.5
JET IMPINGEMENT	1	2	1.5	2	3	2.5
MICROCHANNEL	1	3	2.0	1	3	2.0
PUMPED CAPILLARY EVAPORATOR	2	3	2.5	2	3	2.5

Scoring: 1 = Poor 2 = Fair 3 = Good

3.4.5 Thickness and Lateral Requirements

The microchannel, CHIC, and pumped capillary evaporator have demonstrated thicknesses on the order of 1/2 cm or less. The heat pipe spreader and evaporative spray cooler are each about 1 cm thick. Boiling jet impingement has been developed with greater thicknesses, but thickness reduction is not expected to degrade thermal performance [54]. The heat pipe spreader requires large lateral area; therefore it is best suited for loosely spaced cooling devices.

3.4.6 Other Factors - No discernible differences could be found in the expected lifetime of the various coolers. In Table 4 under "Flexibility and Growth," curved channel flow received a lower than average score. The method envisioned for employing this concept when cooling multiple devices is to construct a sinuous flowpath, with devices mounted above each bend of the flow channel. This method, if employed, restricts device mounting to periodic locations.

3.5 Conclusions - Overall Comparisons

Assessments were made of various cooling technologies for the application of cooling high power avionics devices aboard fighter aircraft. Each concept appears capable of meeting the thermal requirement of removing 100 W/cm^2 of heat flux while maintaining a 90 °C junction temperature. Additionally, each concept ranks highly in certain applications, as attested to by the many uses for the concepts indicated in the references.

General conclusions are given below, with the concepts listed in order of their ranking in the trade study:

1. The CHIC cooler incurs the least system impact. Not only does it incur low TOGW penalty, but it also should be able to use PAO, the aircraft coolant of choice. It has a good manufacturing development status. Tests need to be conducted using PAO to verify performance predictions, and cold start must be addressed in the design.

2. Jet impingement with subcooled boiling and microgroove surface enhancement offers the temperature stability that boiling provides without the need of a condenser. The use of slotted nozzle safeguards against clogging. Development of thinner modules will be required for most avionics uses. Like evaporative spray, this concept requires stocking an extra coolant.

3. Evaporative spray cooling incurs low TOGW penalty. It requires a condenser and the stocking of a dielectric coolant, which add to complexity and maintenance costs.

4. High performance heat pipe heat spreaders have demonstrated adequate heat removal rates and offer low system impact. They require lateral room for heat spreading and are susceptible to acceleration forces.

5. Jet impingement with subcooled boiling and no surface enhancement requires a relatively high flowrate to meet the thermal requirements.

6. Microchannel coolers offer thin construction and should be able to use PAO. Drawbacks include high pressure drop, low coolant supply temperature requirement, and manufacturing complexity if multiple sites require cooling.

7. Curved channel flow with subcooled boiling is still being developed as a way to increase heat flux capability in electronics cooling applications.

8. Pumped capillary evaporators can overcome acceleration forces which limit heat pipes. These systems currently use coolants which are flammable, toxic, or corrosive.

The work reported in this section is also described in [65].

SECTION 4

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